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DYNAMIC SCALING OF ONE-SEVENTH SIZE F-15 PROTOTYPES FOR AGILE FLIGHT SIMULATION

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FOR THE DIRECTOR

Thomas J. Moore

THOMAS J. MOORE, Chief
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13. ABSTRACT *(Maximum 200 words)*
Data from F-15 prototypes, properly dynamically scaled, were delivered to AL/CFBS by Captain Dan Baumann of WL/FIM as a result of the Window on Science Program. The prototypes were run in Israel at the Technion, Israel Institute of Technology by Dr. Ben Gal-Or of the Aeronautical Department. Over 20 runs of data were delivered and they included the Herbst's maneuver, the Cobra maneuver and a host of other agility motion profiles. The moments of inertia that were used to produce the scaling factors included such conditions as the plane having specific levels of bomb loads, as well as three fuel conditions: low fuel, half fuel, and fully loaded fuel. These motion data delivered to AL/CFBS will be used to emulate supermaneuvers on the DES centrifuge motion simulator.

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PREFACE

In August 1989, the concept of agility and supermaneuverability developed substantially new interest to the United States Air Force when the SU-27 (Russian) aircraft demonstrated the "Cobra" maneuver at the Paris Air Show. This maneuver was performed with great controllability and stability and for the first time, it became an important factor to deal with in a potential air combat scenario. Prior to this time fighter pilots referred to the adage, "Speed is Life." This meant that, in a combat scenario, the faster plane would have an advantage. After the August 1989 Paris Air Show, this adage was modified to "Point First and Shoot." This implied that the aircraft which could maneuver quickly, would probably have the advantage in the combat scenario over his opponent. One driving factor to cause this change of priorities to the fighter pilot was the development of advanced weapon systems which only required the aircraft to be pointed accurately before the release of the missile or other armed device.

Prior to August 1989, work had been accomplished on agility and supermaneuverability, but mainly on a theoretical basis. The first computer simulation of an agile profile began with the preliminary concept of supermaneuverability and was due to Herbst in 1972. At that time the question was raised on how to produce a 180 degree yaw pointing rotation of a fighter aircraft in minimum time. The solution led to the "Herbst Maneuver" which actually was a computer solution to a minimum time, yaw pointing problem. This opened up many new investigations on how best to point an aircraft in minimum time for a specific mission objective.

At the Jet Propulsion Laboratory, Technion Israel Institute of Technology (IIT), a study was ongoing involving thrust vectoring of one-seventh size F-15 aircraft. The mission of this study was to investigate various aspects of thrust vectoring that may improve the pointing capability of F-15 type aircraft. When the Director of the Jet Propulsion Laboratory (Dr. B. Gal-Or) gave a talk at Wright-Patterson Air Force Base in 1989, it became obvious that the F-15 prototypes could yield data on the stress fields a pilot and equipment may be exposed to during agile flight maneuvers. This type of information is of interest to Armstrong Laboratory to improve the use of the DES centrifuge as a motion simulation device.

One problem, however, with the F-15 prototypes being flown in Israel was that they were one-seventh the linear size of an F-15 but their mass and polar moments of inertia characteristics were not scaled proportionally. The purpose of this research effort was to properly scale the prototypes so that the dynamic response of the aircraft being tested in Israel would provide valuable and realistic data to Armstrong Laboratory on the types of linear and acceleration stress fields a pilot would experience in the agile flight environment. It was required for this research effort to deliver to AL/CFBS the scaled acceleration profiles to help in the simulation of motion fields on the DES centrifuge.

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INTRODUCTION

The early work of Herbst, et al. [1-3] provided a new concept in tactics for aircraft combat. In his scenario, it was suggested that the objective was not to fly as fast as possible, but rather to maneuver quickly and become "rapidly pointed" at the opponent aircraft. Prior to this time, the aircraft with the greater speed was considered to have the advantage in combat tactics. When the new weapon systems became developed in the 1980s, it became even more desirable in combat scenarios to just point the aircraft. The new weapon systems that had evolved at that point in time could then track the opponent and deliver the weapons armament.

One manner to rapidly point an aircraft is with the assistance of thrust vectoring. Dr. Ben Gal-Or of the Technion Israel Institute of Technology (IIT) had developed a program in thrust vectoring [4,5] and had a research facility and laboratory in Israel prior to 1989. One of the motivations for this research effort was that the military utility of enhanced agility using vectored propulsion was not well understood [6] and studies needed to be conducted to enhance our understanding of how this radically new stress environment may affect the pilot. Also with the advent of digital flight control and computer assisted engine control technologies, airframe and propulsion system designers found a much higher degree of coupling between the aircraft and its engine for the high performance aircraft. The work of Dr. Ben Gal-Or continued into the 1990s with a focus on a number of issues including the shape of the aircraft [7], the placement of the thrust vectoring vane actuators, and a host of other investigations.

In the 1980s, aircraft agility became a topic of great interest [8,9,10,11,12,13] and the demonstration of the "Cobra" supermaneuver [14] at the Paris Air Show in 1989 intensified this interest to the United States Air Force. An issue of importance is that present fighters can be made to fly these unusual flight maneuvers by several known methods: using a high angle of attack (alpha > 50 degrees), thrust vectoring, vortex manipulation for control, or possibly using differential deflection of stabilizers or canards. There are also the issues of structural problems and controllability associated with flying an aircraft in this unusual flight regime.

In studying the problem of controller design in these particular flight scenarios, Chiang et al. [15] had addressed such a problem in comparing the tradeoff between controllability and stability. He studied the FA/18 when it was considered using thrust vectoring to produce supermaneuvers with this aircraft. In a previous study, Kalviste [16] had shown that a pilot must control both the standard P and Q angles simultaneously to change the aircraft's body axis roll angle. This is because neither the body X-axis nor the velocity vector (wing X axis) can be used as the roll-axis reference. Both these variables change directions themselves during the supermaneuver.

It then became an important Air Force need to develop fixed base methods to simulate these types of motions on flight simulators like the DES centrifuge [17]. The cost effectiveness of these simulations is quite apparent. For example to simulate a supermaneuver on a fixed base system like the DES centrifuge may cost $2,000 a day. For aircraft like an F-15 or F-16, this cost rises to $10,000 per flight hour. To actually flight test using an experimental aircraft like an X-31 or an F-22, this cost may then rise up to $100,000 per flight hour, thus precluding only the most mission essential studies to be flight tested. Since large resources are at risk, it is necessary to first delineate which of the issues need be studied related to supermaneuverability in order of importance to the Air Force. This further motivates and focuses only the most relevant investigations on both pilots and equipment to be conducted on simulators like the DES centrifuge motion simulator.

Issues to be Studied Related to Supermaneuverability

Before the details are presented describing the research effort performed in Israel, it is important to briefly enumerate on a number of research questions related to what type of problems or situations exist in the supermaneuverable flight regime and what is the influence of these obstacles on a pilot. This clearly motivates the need to perform only very focused studies on fixed base motion simulators like the DES centrifuge simulator. We list the most important factors that are known to presently influence the agile flight scenarios that are generated.

(1) Minimizing the Thrust to Weight Ratio

One important consideration in designing an agile aircraft (analogous to the design of a sports car in a race or other situation in which both speed and maneuverability are important) is related to the desire to have a vehicle with the greatest thrust and with minimum weight or inertia. These requirements would provide the fighter aircraft with greater range and versatility. Also it is plausible to presume that greater thrust, concurrent with minimum weight or inertia, will result in an increase of the net accelerations that can be realized. This increase of net accelerations that can be developed is consistent with an aircraft being highly agile and maneuverable.

(2) Design of New Maneuvers Over Conventional Types

If modern aircraft are to fly radically new maneuvers, one needs to investigate, a priori, what candidate flight trajectories are viable for study. When the candidate maneuvers are known, one could then simulate the acceleration profiles produced in the aircraft on motion simulators like the DES centrifuge and compare how they stress the pilot and possibly compromise his performance. The Standard Evaluation Maneuver Set (STEMS) program [18] was an attempt to comprehend this problem. It was a computer based system and represented one of the first of these efforts to quantify the class of maneuvers that may be candidates for agile maneuvering and thus future studies in human stress research.

(3) Transient and Complex G Stress Scenarios

In Dr. Gal-Or's book [5], he describes supermaneuverability as the "breaking of the stall barrier." This is a radical departure from the conventional tactics thinking of combat pilots whereas the pilot would be exposed to a new host of complex accelerations and transient type of forces. Thrust vectoring capabilities of modern aircraft, like the F-22, provide this rapid change of orientation a pilot may wish to command during the performance of a combat mission. Thus, it is important to understand the extent of the magnitudes, direction, and other characteristics of the new transient acceleration conditions that appear in this new operational environment and how this stress setting may affect the pilot and equipment. A survey was conducted on the possible range [19,20] of stress profiles that might affect pilots. This provided a new direction in acceleration research, whereas the pilot would now be exposed to a new dimension of acceleration research, thus requiring a more modified definition of the envelope which describes the human's acceleration stress environment from the traditional sustained acceleration studies previously performed.

The purpose of the survey in [19] was to examine extant data on all types of complex acceleration fields that a pilot has been exposed to previously. Four major sources were considered: (1) Data from X-29 flights, (2) Analysis of videotapes of the 1989 Paris Air Show, (3) F-15 prototypes flown in Israel, and (4) A review of all extant literature related to motion simulators. Using Gx, Gy, and Gz to represent body axes accelerations (Gx is eyeballs in, Gz is down the spine, and Gy is positive to the left shoulder) and with the use of p, r, and y to denote body pitch, roll, and yaw axes, the following table lists the results of the four surveys with the right most column of Table 1 denoting the worst case scenario as a range of values. This was also reported in [19].

Table 1. The Human Complex Stress Envelope in Agile Flight

Variable	Source 1	Source 2	Source 3	Source 4	Worst Case Range
Gx	0.6, 0.4	2.2, -2.5	0.3, -1.7	6.5, -6.5	6.5, -6.5
Gy	0.7,-.16	0	-	4, -4	4, -4
Gz	3.6, .41	3.0, -1	7, -2.	9.5, -2	9.5, -2
$\dot{G}x$	-	-	-	± 5	± 5
$\dot{G}y$	-	-	-	± 2	± 2
$\dot{G}$	-	-	-	± 5	± 5
$\dot{\Theta}_p$	11, -34	120,0	180,-170	± 90	180,-170
$\dot{\Theta}_p$	289,-253	38, -38	-	± 10	289, -253
$\dot{\Theta}_r$	25, -34	30,0	-	± 90	90, -150
$\ddot{\Theta}_r$	289, -253	20, -20	-	± 10	289, -253
$\ddot{\Theta}_y$	4, -27	0	0	± 90	± 90
$\ddot{\Theta}_y$	69, -68	0	0	± 10	68, -68

The dots above the variables indicate time derivatives and all angular measures are in degrees. Thus, a new complex stress field scenario now defines the stresses the pilot is exposed to in the agile flight regime.

(4) Stealth and the "Low Observable" Issues

Another factor which produced the rise of interest of pilots to agility maneuvering was the increase of the ability of an aircraft to provide an atmosphere of stealth in the combat scenario. This is sometimes termed having "low observables," which refers to the ability of a fighter aircraft to maintain low profile visibility. One method to generate this stealth characteristic is through the use of "Cold Propulsion." This is a new aerospace propulsion technology whereas an aircraft can ignite its engines at a much lower temperature, thus providing a low infrared signature (IR). Thus, the aircraft appears to be in the BVR (beyond visual range and also beyond detection) area a larger proportion of the time and has increased stealth properties with respect to the opposing aircraft. When two competing aircraft fly in such a scenario, this situation exists until the aircraft suddenly comes in close range and abruptly become aware of each other's presence. This end game scenario is termed "fighting in a phone booth" and refers to the scenario whereas both pilots become immediately aware of each others presence and are required to instantly maneuver. Thus, agility in this scenario is the only tactic possible to survive under these conditions. Thus, stealth and the property of having "low observables" characteristics provides a forum for the existence of agility type maneuvers to study for both pilots and equipment.

(5) The Definition of Agility, Supermaneuverability, and Supercontrollability

Once the Air Force became cognizant of the need to perform studies of highly maneuverable aircraft, one of the first issues to be addressed concerns what types of maneuvers are considered to be agile and what benefits are derived, thereupon, with their use. Aerodynamicists [21,22] have always been interested in the investigation of many fruitful areas of theoretical inquiry that will help define the class of acceptable maneuvers. These maneuvers must have some advantage in the combat scenario. The motivation for studies of this type was based on the manner which the original Herbst's Maneuver [1-3] was developed. It was from an optimization procedure and a computer solution that this first supermaneuver was discovered. Another way to design these aircraft trajectories takes into consideration the concept of energy analysis.

(6) Energy Analysis and its Effect on Agile Flight Scenarios

Another way to view agile flight scenarios is through an energy analysis of the aircraft trajectories that result. For example, one can view the Herbst's maneuver (Figure 1) and the Cobra Maneuver (Figure 2) as an exchange of the kinetic energy of linear movement into an increase of potential energy as the aircraft gains altitude, loses speed, and practically stalls (but rapidly changes its pointing direction). Briefly what is occurring in the Herbst's maneuver, when analyzing this scenario, is that the pilot is really converting his linear kinetic energy of motion into potential energy which manifests itself by a slowing down of the aircraft and resulting in an increasing altitude. These concepts easily extrapolate to other frame coordinates to design these trajectories such as in the roll and yaw axes.

Typical maneuver for post-stall maneuvering illustrates enhanced fighter maneuverability advantage over conventional aircraft (with 20-degree angle-of-attack capability). Note much smaller turn radius demonstrated by aircraft with supermaneuverability (90-degree angle-of-attack capability).

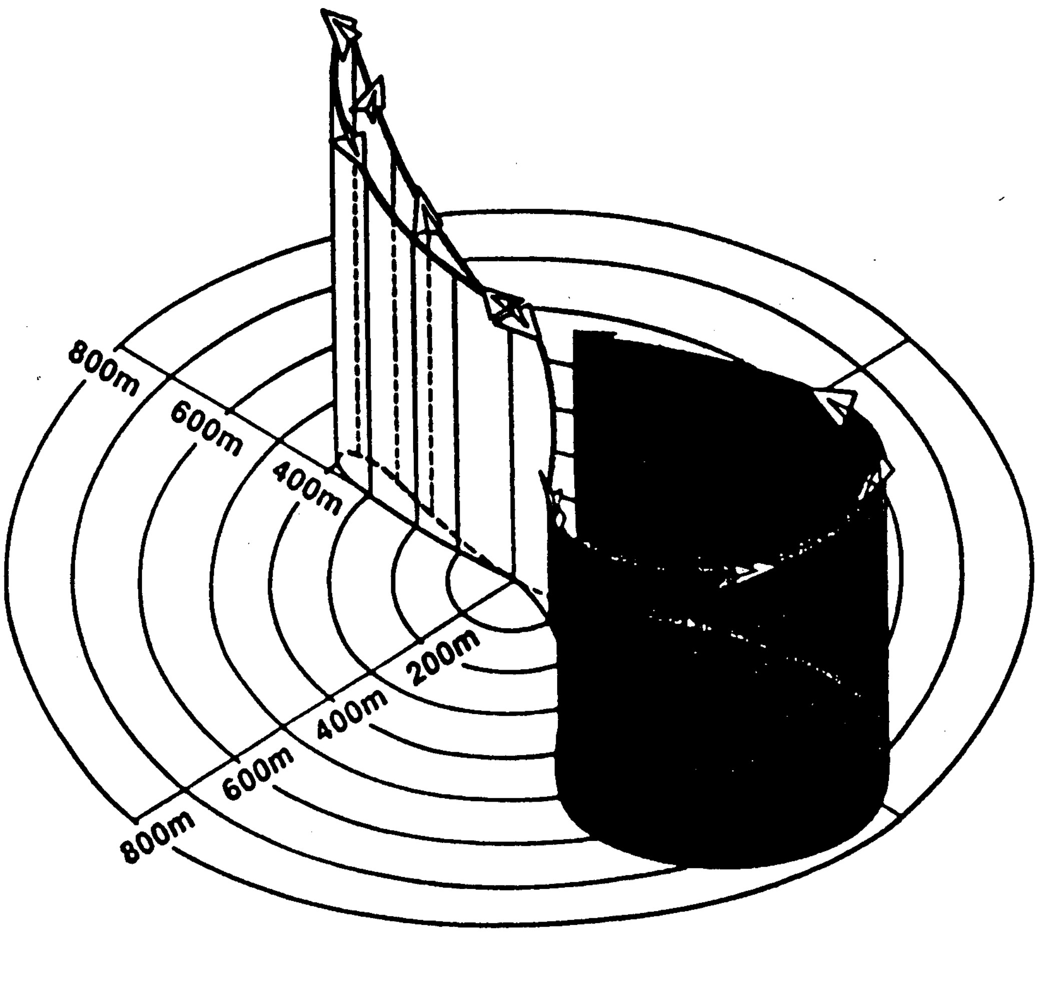


Figure 1. The Herbst Maneuver

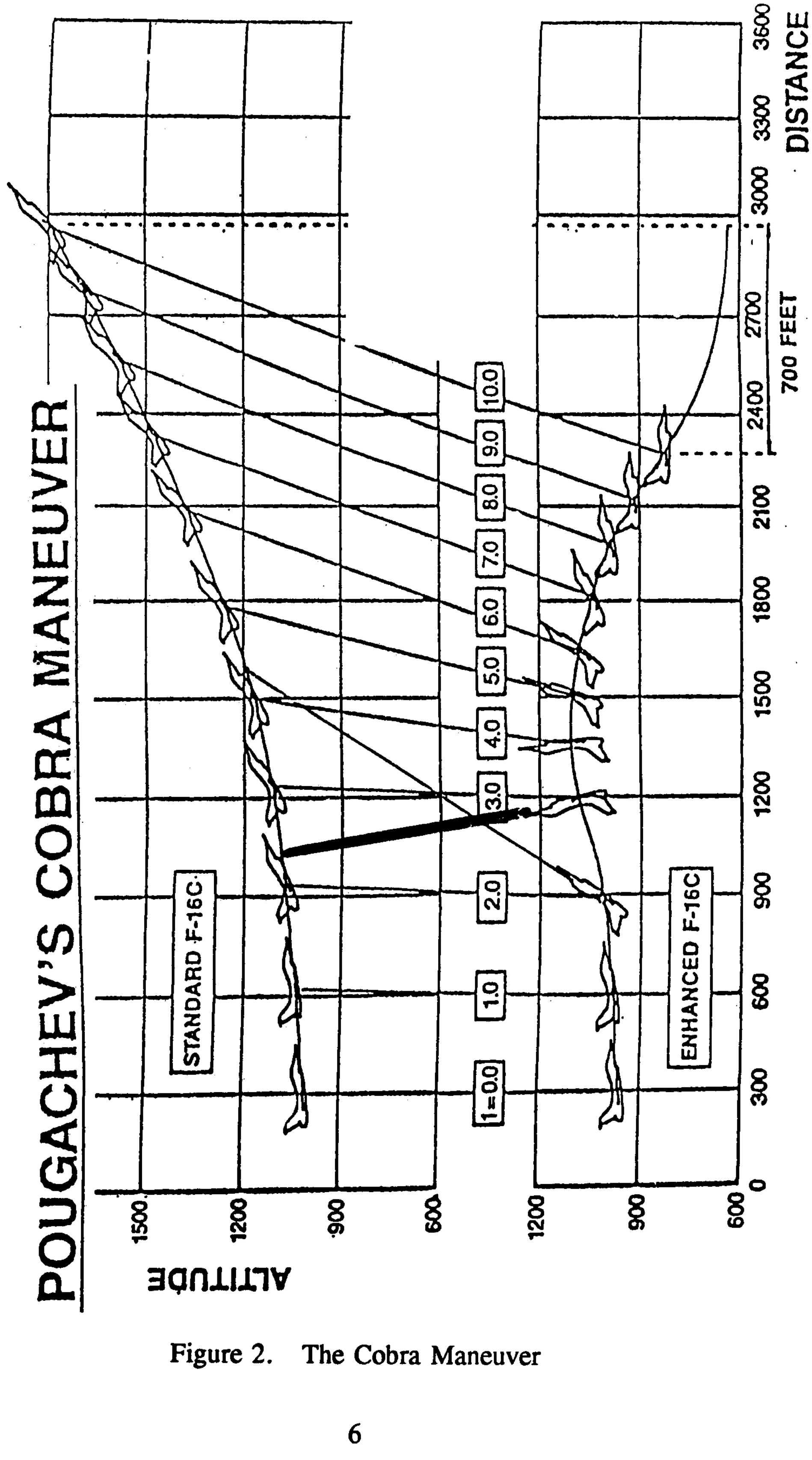


Figure 2. The Cobra Maneuver

(7) Multi-Axis Agility - Pitch, Torsional, and Axial

Most of the efforts discussed so far refer to the "Cobra" and "Herbst" type maneuvers which essentially are forms of pitch agility. The Herbst maneuver, however, appears to have a yawing motion (from a God's view perspective) but in actuality, is performed by a roll about the velocity vector of the aircraft near the apex of the maneuver (Figure 1). The velocity vector is a vector describing the movement of the center of mass of the aircraft. The pointing angle of the aircraft refers to the vector characterized by a direction along the longitudinal axis of the aircraft. The angle of attack (alpha) refers to the angle difference between the velocity vector and the corresponding pointing vector of the aircraft. Most of the discussion so far has only described pitch type agility maneuvers; however, these discussions easily extrapolate to other axes.

Other types of aircraft agility exist and have such terms as "torsional" and "axial" agility. They refer to the ability of an aircraft to maneuver in a roll or yaw direction similarly with the same type of movement characteristics that have been previously discussed for the pitch axis. Thus, the research reported herein has additional applicability in other scenarios, but for simplicity of discussion the pitch type maneuvers are considered in the material to be presented in the sequel. The issues discussed so far have not included dynamic type response properties associated with agile flight, e.g., which may include time delays in actuating the thrust vectoring. Such maneuvers can be developed through optimization procedures [23,24,25] similar to the derivation of the Herbst's maneuver, but in other axes.

(8) Impact of Dynamics and Actuator Time Delays on Agility Maneuvers

Most of the issues discussed up to this point relate to kinematics type considerations. It is also important to consider the dynamics properties of fighter aircraft and how they may influence agile flight. When a pilot commands a motion, the actual dynamic response of an aircraft may lag in time significantly behind the initial command input made by the pilot. This will occur in aircraft performing agility maneuvers as well as in any other dynamic system. One manner to characterize lags in dynamic response is by using pure time delays. Time delays, however, are known to cause perceptual problems with humans and may result in a catastrophic effect termed pilot induced oscillation (PIO) [26]. Problems related to PIO can be considered a contributing factor in many aircraft accidents and had an influence on the crash of the YF-22 [27]. This situation occurred during the flight testing of this very complex thrust-vectoring system and its cause is still under investigation. Thus, time delays due to any source (including delayed or poor visual information or possibly system response delays) are problems that have to be dealt with. In the agile flight environment, they will certainly only compromise an aircraft's agility characteristics. With these main issues of agility enumerated, the next step is to outline the overall program to produce important data related to agile motion profiles for delivery to the Armstrong Laboratory from the Jet Propulsion Laboratory, at the Technion, Israel Institute of Technology (IIT). The goal of development of this data base is for motion simulation on the DES centrifuge agile flight maneuvers to study both pilots and equipment in this scenario.

The Israel Effort - Part I - The Window on Science Visit

Funds were first received ($65,000) from an ILIR (In-house Laboratory Innovative Research) program at Armstrong Laboratory to help develop agile motion profiles using the one-seventh size prototypes that existed at the Technion, IIT, Jet Propulsion Laboratory. At that point in time, a Captain Dan D. Baumann of WL/FIM became interested in becoming a liaison person to go to Israel to monitor the laboratory testing and to eventually return the data to Armstrong Laboratory. Captain Dan Baumann would use a version of the Window on Science (called Window on Europe) program to travel to Israel. He was stationed at WPAFB and obtained three trips to that country and remained about 30 days during each trip. He became acquainted with the laboratory facilities, as well as participated in the prototype testing. Captain Baumann also had a unique background to act in this capacity. He received his Masters of Science degree in Aeronautics and Astronautics from The Air Force Institute of Technology and his thesis topic involved "Flat Spins of F-15s" [37]. His expertise involved F-15s and he had used the polar moments of inertia of the F-15 in his thesis. Special permission had to be obtained to give these numbers to the Israel group. His thesis topic discussed the flat spin dynamics of F-15s during this uncontrollable maneuver. The technical contribution of this thesis at AFIT was to investigate means of producing control action to these aircraft when they were put in these untoward flight scenarios.

As a consequence of the three trips by Captain Baumann to Israel, he participated in the testing of the one-seventh size prototypes and he documented the details of his interaction with IIT via trip reports. Each trip report [28] contained status narrations of the different efforts made at IIT during the testing. From his reports, one can summarize how they attacked the problem of dynamically scaling the prototype F-15s:

(1) Captain Dan Baumann, working in conjunction with Dr. Ben Gal-Or and his research assistants, had agreed on the proper equations of motion to describe dynamic scaling. These technical details are covered in the next section of this report.

(2) Measurements of the polar moments of inertia were made in the three axes of the F-15 prototypes at the laboratory of IIT. To calculate the polar moments of inertia, these measurements were made by applying a torque input to the prototype in each axis and measuring the net acceleration that resulted from that particular rotational axis. To determine the polar moment of inertia, one uses:

$$\text{Torque}_{(ii)} = I_{(ii)} \ \text{alpha}_{(ii)} \qquad (1)$$

Where $I_{(ii)}$ is the polar moment of inertia in the axis (ii), and $\text{alpha}_{(ii)}$ is the resulting acceleration measured from the measured, applied torque, $\text{Torque}_{(ii)}$.

(3) All data and analysis were developed in a Quatra Pro program. In addition, data collection was accomplished using a portable notebook computer (386 IBM based) and data were downloaded from the prototype computer after a run for storage into the notebook computer.

(4) The prototypes were then run in flight test. A member of the IIT group maneuvered the aircraft via remote control through specific maneuvers to emulate the "Cobra," the "Herbst" maneuver, and a variety of other supermaneuvers.

(5) The data collected onboard were then downloaded to the notebook computer for further analysis.

(6) As a post-hoc analysis, the data were then dynamically scaled using Quatra Pro and then transferred to floppies which were delivered to Armstrong Laboratory.

Captain Dan Baumann's Window on Europe visit allowed him to interact in parts (1)-(6) above and provided a valuable service to AL/CFBS in monitoring the experiments conducted in Israel, as well as help deliver data to AL/CFBS.

The technical issues of Dynamic Scaling need to be discussed. This was the primary technical aspect of the program and was one of the main reason why AL/CFBS was involved in this program.

Procedures for Dynamic Scaling

The objective of this research effort was to extract data from a prototype model and to predict how an actual aircraft will respond in certain dynamic conditions. This is particularly important as data are collected from the prototypes on G accelerations. These data <u>must</u> be appropriately scaled to give the actual accelerations the aircraft would achieve.

Dynamic scaling refers to one class of problems that are derived from studies on verisimilitude. As displayed in Figure 3a, a prototype has certain polar moments of inertia ia1, ia2, and ia3 which can be determined from simple laboratory tests as described in the prior section.

In Figure 3b, the actual aircraft of interest (an F-15) is displayed. It is similar in linear dimensions (i.e., it is exactly 7 times the linear lengths of the prototype) but the polar moments of inertia Ia1, Ia2, and Ia3 do not necessarily scale upward 7 times.

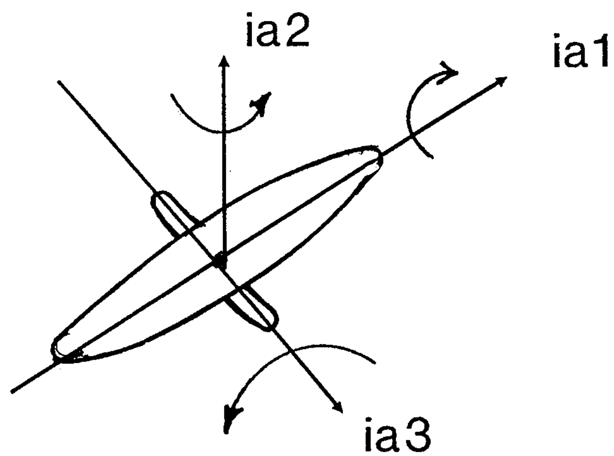


Figure 3a. The Prototype - Polar Moments of Inertia

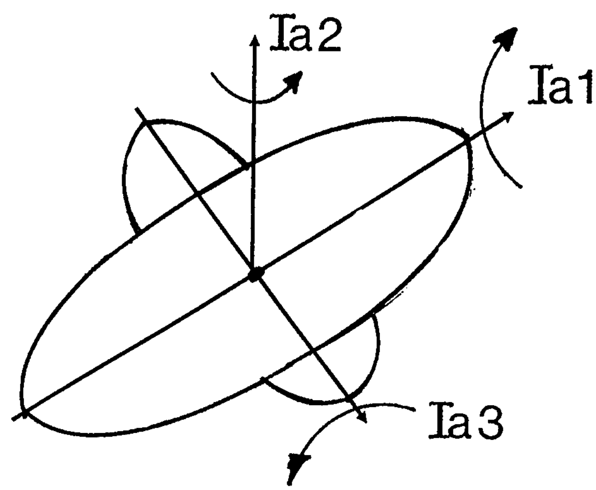


Figure 3b. The Actual F-15 - Polar Moments of Inertia

As a very simple approximation, the scaling factors:

$$K1 = Ia1 / ia1 \quad (2)$$
$$K2 = Ia2 / ia2 \quad (3)$$
$$K3 = Ia3 / ia3 \quad (4)$$

may not be equal. In addition, these scaling factors may not be constant and vary due to a host of other conditions including fuel load of the aircraft, its armament, the altitude and speed values, and other factors. If the scale factors K1, K2, and K3 were known, there exists two ways to make the data obtained from the prototypes represent that from an actual F-15 aircraft.

Method I - Using Radius of Gyration Effects

Once the scale factors K1, K2, and K3 are known (at least at one point in time), one can use a "Radius of Gyration" method to properly scale the prototype. In this situation, point masses are added to the prototype such that the dynamic response of the prototype will replicate, precisely, the response of the actual aircraft.

To better understand this concept, the prototype is modeled as a pair of point masses m1,m2, and m3 in Figure 4a. The respective Radius of Gyrations are R1, R2, and R3, respectively. Thus, the polar moments of inertial in Figure 4a can be written:

$$ia1 = m1 \quad R1^2 \quad (5)$$
$$ia2 = m2 \quad R2^2 \quad (6)$$
$$ia3 = m3 \quad R3^2 \quad (7)$$

In order to correct this mismatch between the dynamic response of the prototype to the dynamic response of the actual aircraft, additional masses (perhaps negative) m1', m2', and m3 ', are added as displayed in Figure 4b. These masses are placed at a distance R1', R2', and R3' from the origin, as indicated. This now scales each moment of inertia in each axes accordingly. Consequently the modified prototype will dynamically response similar to the actual aircraft.

Method II - Simply Scale the Prototype Data

A second method to achieve dynamic scaling would be to just determine the scale factors K1, K2, and K3. These factors may vary with time, aircraft, and aerodynamic conditions. Data could then be collected from the prototype with its original inertia and then just simply corrected by scaling the data. This is the preferred method because it is extremely difficult to keep the prototypes flying and equipment had to be constantly added onboard to collect data, thus constantly changing the prototype's inertia characteristics.

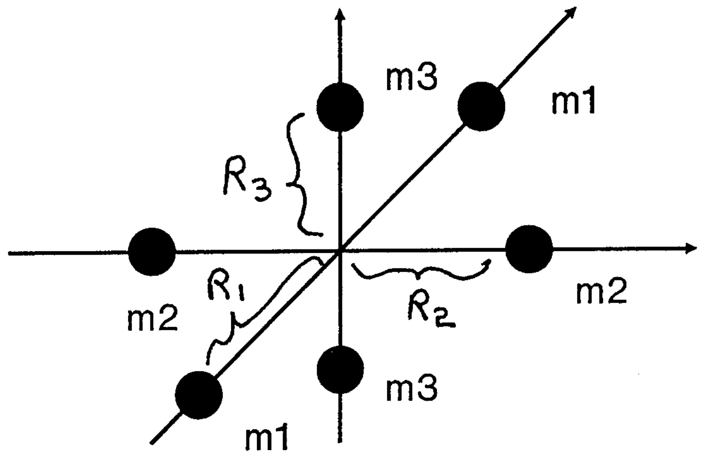


Figure 4a. Prototype Before Scaling - Radius of Gyration Point Mass Assumption

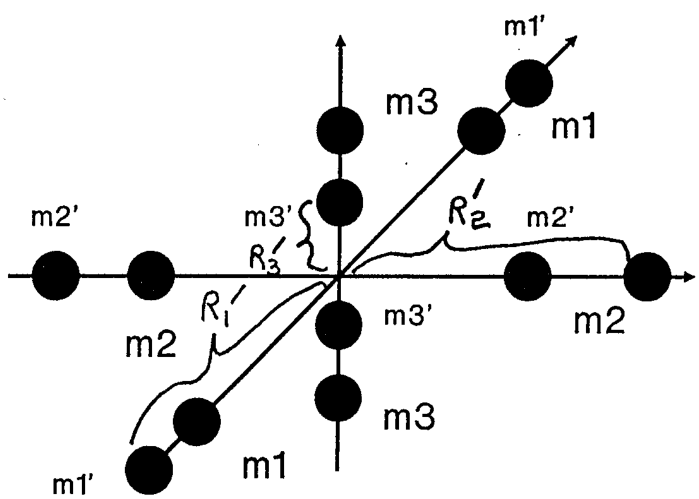


Figure 4b. Prototype After Scaling - Radius of Gyration Point Mass Assumption

Determination of Scale Factors

The present methods of performing verisimilitude studies, including dynamic scaling, are constantly being researched today. Within the United States Air Force, a particularly well accepted reference was that by Woodcock [29]. This classic report describes some of the most important issues related to dimensional analysis and dynamic scaling. At least four primary factors need to be considered to properly describe dynamic scaling:

(1) Froude Number (relates inertia force to gravity force).

(2) Reynolds Number (ratio of inertia force to viscous force)

(3) Lift Coefficient (the same as angle of attack) = C_L

(4) Normal accelerations.

In [29], Woodcock derived scale factors K1, K2, and K3 in terms of other parameters such as air density, length ratios, velocity ratios, gravity, kinematic and dynamic viscosity, and boundary layer height. Some other factors that will also influence these scale factors are the level of fuel load the aircraft maintains and the armament load the aircraft may carry during the mission. All these factors influence the dynamic response of the aircraft, and hence its agility.

In Reference [29] various scenarios are discussed for dynamic scaling. The scale factors K1, K2, and K3 can be determined based on several considerations:

(1) Maintain a match of the Froude numbers between the prototype and aircraft (this implicitly implies a velocity ratio scaling).

(2) Maintain a match of the Reynolds' number between the prototype and the aircraft.

(3) Match both Froude number and C_L - The coefficient of lift.

(4) Match both Reynolds' number and C_L .

(5) Match Froude number, normal accelerations and C_L .

(6) Other combinations of these variables are possible.

Thus, the dynamic scaling problem is predicated on whatever criteria are selected as important for the mission at hand. The particular method finally decided upon by Dr. Ben Gal-Or and his researchers at IIT included matching of geometric parameters, matching relative airstream density, and maintaining equivalences of Froude numbers.

Although there are some problems with these assumptions [30-31], it nevertheless was consistent with our goal of replicating supermaneuvers in flight. Dr. Ben Gal-Or documented these results in a journal article [32].

Next a discussion on the flight testing procedure conducted at the IIT to procure the data is given. This information has been reported in a host of references [33-36], presented from the perspective of Dr. Ben Gal-Or of the IIT.

The Israel Effort - Part II - Flight Testing of Prototypes

From the IIT perspective, this research effort was broken up into seven distinct tasks:

Task 1 - Add accelerometers and noise filters to the prototypes to extract good flight test data.

Task 2 - Measure the three acceleration time histories (Gx,Gy,Gz) sampled at 20 Hz. Also collect the following data: velocity, angle-of-attack, sideslip angle and yaw, roll and pitch angular velocities and accelerations, as well as the pilot's command inputs. These latter data were sampled at 40 Hz.

Task 3 - To develop a new, expanded post stall thrust vectoring performance envelope of the aircraft. This was a requirement from the Armstrong Laboratory to characterize, in some manner, the overall capability of the aircraft in an agility sense.

Task 4 - Perform some standard agility comparison maneuvers including the negative and positive Cobra maneuvers and the Herbst's maneuver.

Task 5 - Provide test data for use in the centrifuge simulator at WPAFB (the DES or dynamic environment simulator).

Task 6 - Develop intermediate reports to communicate the ongoing efforts, their problems and successes.

Task 7 - Deliver data to Armstrong Laboratory with videotapes and to graph all relevant results.

The following events led up the prototype flight tests:

(1) Improved thrust-vectoring nozzles (pitch plates) were developed to improve the maneuverability of the prototypes.

(2) Three calibrated accelerometers were added to the prototypes located at the pilot's head location. Later, since vibration problems occurred and interfered with the acceleration readings, three gyroscopes were installed. The excessive weight of the gyroscopes required recalibration of the polar moments of inertia.

(3) Polar moments of inertia of the prototypes were determined from laboratory tests.

(4) Wind tunnel tests verified that the prototypes had appropriate lift and stability characteristics prior to flight test.

(5) Finally, flight testing of prototypes with collection of data were performed with specific supermaneuvers.

(6) Videotaping of the successful runs was accomplished.

(7) Data from flight test were downloaded to a 386, 25 MHz notebook computer using Kermit. It took 2.5 minutes to download data from each run in this manner.

It is noted that the prototypes used were one-seventh linear scale but they only weighted 37 pounds. This weight is 1/1000 of an F-15, but 1/7th the linear size. Thus, the need for dynamic scaling is obvious.

Figure 5 illustrates several of the researchers at the runway of the flight test facility (Meggio Airfield). Figure 6 illustrates the laboratory facility in which the polar moments of inertial were calculated, as well as where the wind tunnel testing was accomplished.

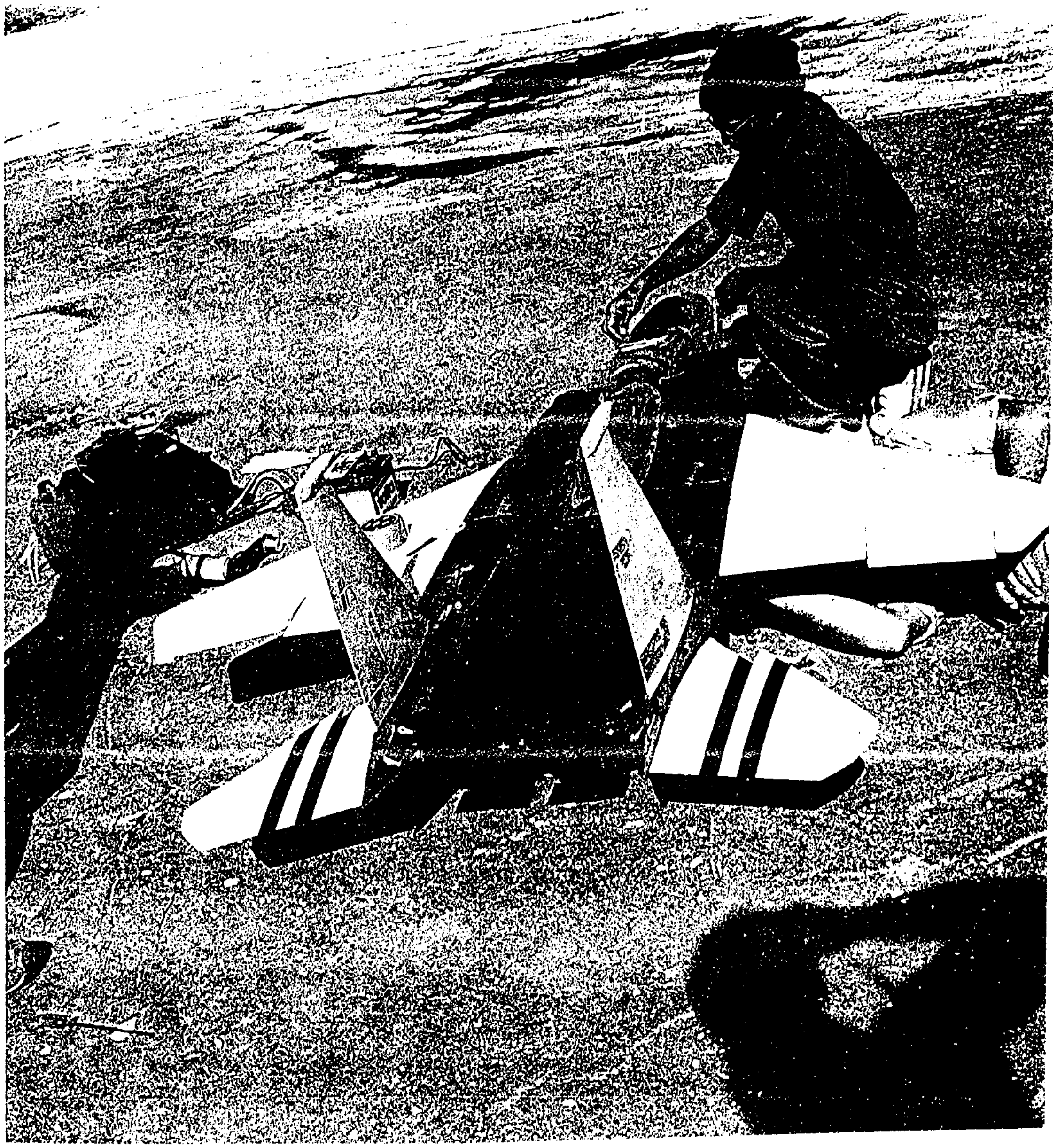
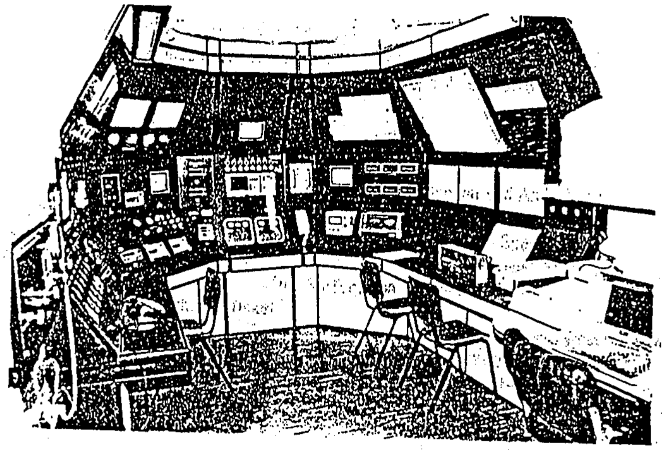
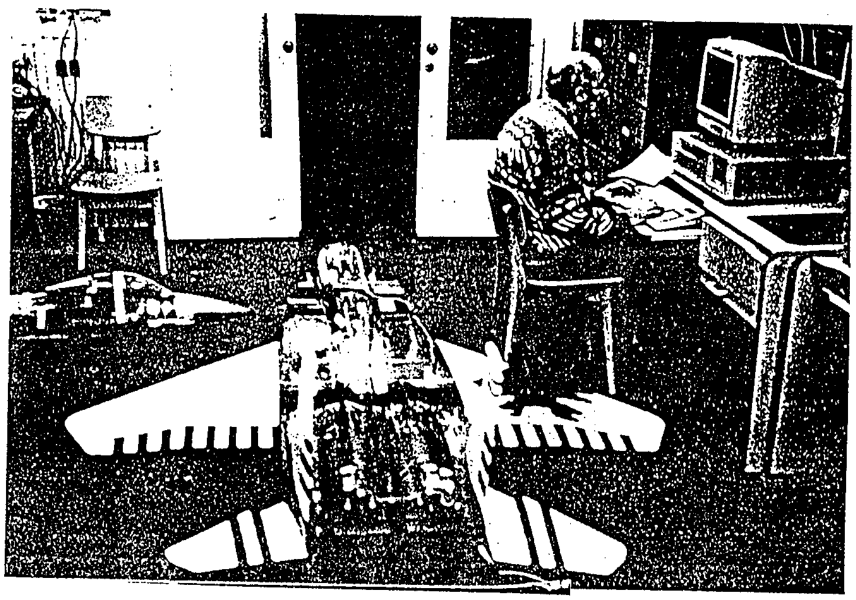


Figure 5. Research Team at Meggio Airfield



Control Room # 3



Parameter Evaluation

Figure 6. Laboratory Testing Facility at Technion

RESULTS

There were a number of problematic areas of the research study which are important to document before all results are stated:

(1) There existed strong coupling phenomena between pitch rates and roll rates, largely due to gyroscopic forces and/or control surfaces trim/deflections to counterbalance initial asymmetric drag/moments at low angle of attack. The two types of coupling can be classified into kinematic and aerodynamic effects. The manifestations of these effects could be distinguished.

(2) Prototypes frequently crashed.

(3) The pilots (on the ground) had to be frequently trained to learn to maintain good control of the prototypes in the air.

(4) Visual problems sometimes occurred when the ground pilot could not clearly see the prototype.

(5) Data were sometimes lost from a run.

The data collected and delivered to Armstrong Laboratory consisted of ten maneuvers. These maneuvers can be classified as follows:

(1) Two elevator-only pitch-up-down simulated air combat maneuvers (SACOMs).

(2) Two vector-only pitch-up-down SACOMs.

(3) Two mixed elevator/vector pitch-up-down SACOMs to maximize agility.

(4) One "half-stick" mixed elevator/vector pitch-up-down SACOM.

(5) One "third-stick" mixed elevator/vector pitch-up-down SACOM.

(6) One turn-back, post-stall, Herbst maneuver via mixed conventional/vectoring means.

(7) One turn-back conventional maneuver via ailerons and elevators, conducted just after the Herbst-type maneuver.

In addition to a derivation of the equations of motion of the aircraft given to Armstrong Laboratory, the measured polar moments of inertia of the prototypes were given. Table 2 lists these values (The weight of a prototype was 14.2 Kg with fuel; it was 13.4 Kg without fuel.):

Table 2. Polar Moments of Inertia - Prototypes

No Fuel	With Fuel
Ixx = 0.596 Slug-FT ^{2}	Ixx = 0.646 Slug-FT ^{2}
Iyy = 3.70 Slug-FT ^{2}	Iyy = 3.76 Slug-FT ^{2}
Izz = 4.09 Slug-FT ^{2}	Izz = 4.18 Slug-FT ^{2}

The corresponding polar moments of inertia for an F-15 are known but such data have restricted access. One source would be Baumann [37].

A more specific listing of the data delivered to the Armstrong Laboratory is now given which represents one of the most important deliverables of this research effort.

Data Delivered to Armstrong Laboratory

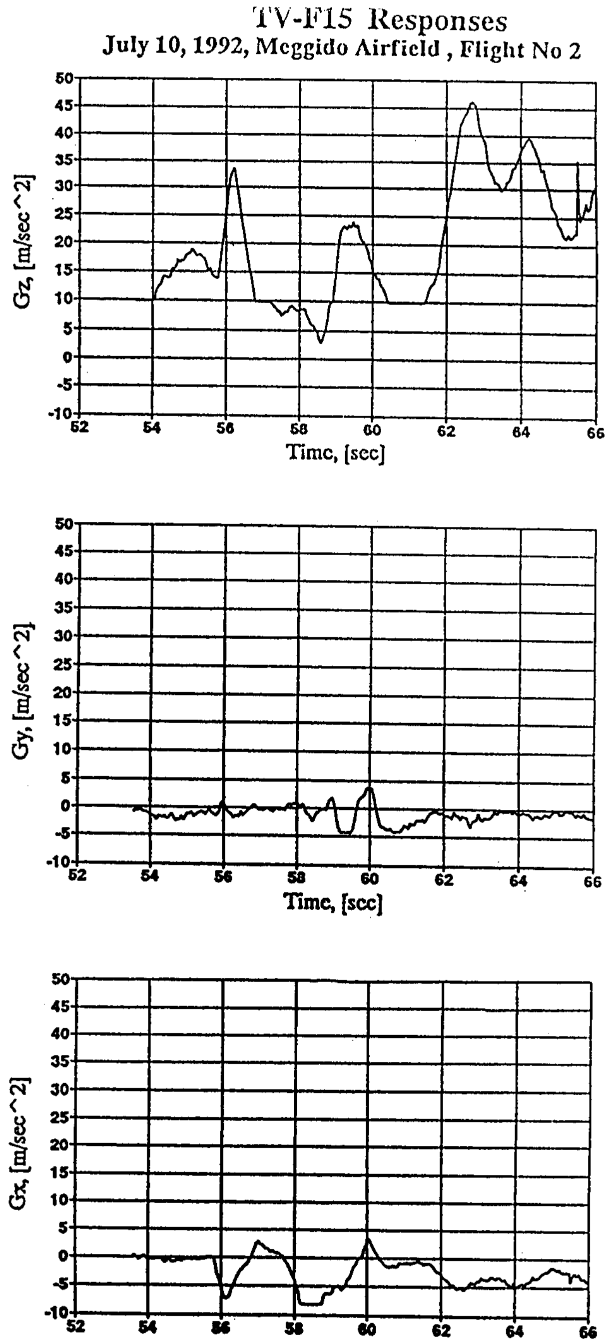
The data from the ten runs described in the previous section was delivered to AL/CFBS on 3-1/2 inch IBM compatible floppy disks. These data could then be opened up in Quatra Pro and easily accessed.

Also delivered were the moments of inertia for the prototypes (with and without fuel), the physical location of all sensors (gyroscopes and accelerometers) to measure roll, pitch, and yaw variables, and the corresponding three linear variables. For the ten runs described in the previous section, the following data channels were of interest to the Armstrong personnel:

Table 3. Final Data Delivered to AL/CFBS

Channel	Measured Variable
0	Roll Gyro + values
1	Y Axis Accelerometer + values
2	Roll Gyro − values
3	Y Axis Accelerometer − values
4	Y Gyro − values
5	Z Axis Accelerometer + values
6	Yaw Gyro + values
7	Z Axis Accelerometer − values
8	Pitch Gyro + values
9	X Axis Accelerometer + values
10	Pitch Gyro − values
11	X Axis Accelerometer − values
12	Alpha (Angle of Attack)
13	Velocity (Probe compensates for alpha only)
14	Beta (sideslip)

The duration of the runs varied from a minimum of 10 seconds to over 120 seconds per maneuver. The data were sampled at 40 Hz, thus creating a massive file of data. To illustrate a representative, but very small part of these data, Figure 7 displays Gz, Gy, and Gx from a Herbst's maneuver. Figure 8 illustrates these G vectors for a pitch SACOM (similar to a Cobra), and Figure 9 illustrates data from maneuvers more representative of a "Cobra."



Histories of the G-Loads on the Pilot During the Turn-Back [Herbst] Maneuver. [2-nd maximum Gz can be reduced by delaying the last pitch-up commands]

Figure 7. Herbst Type Maneuver - G Profiles

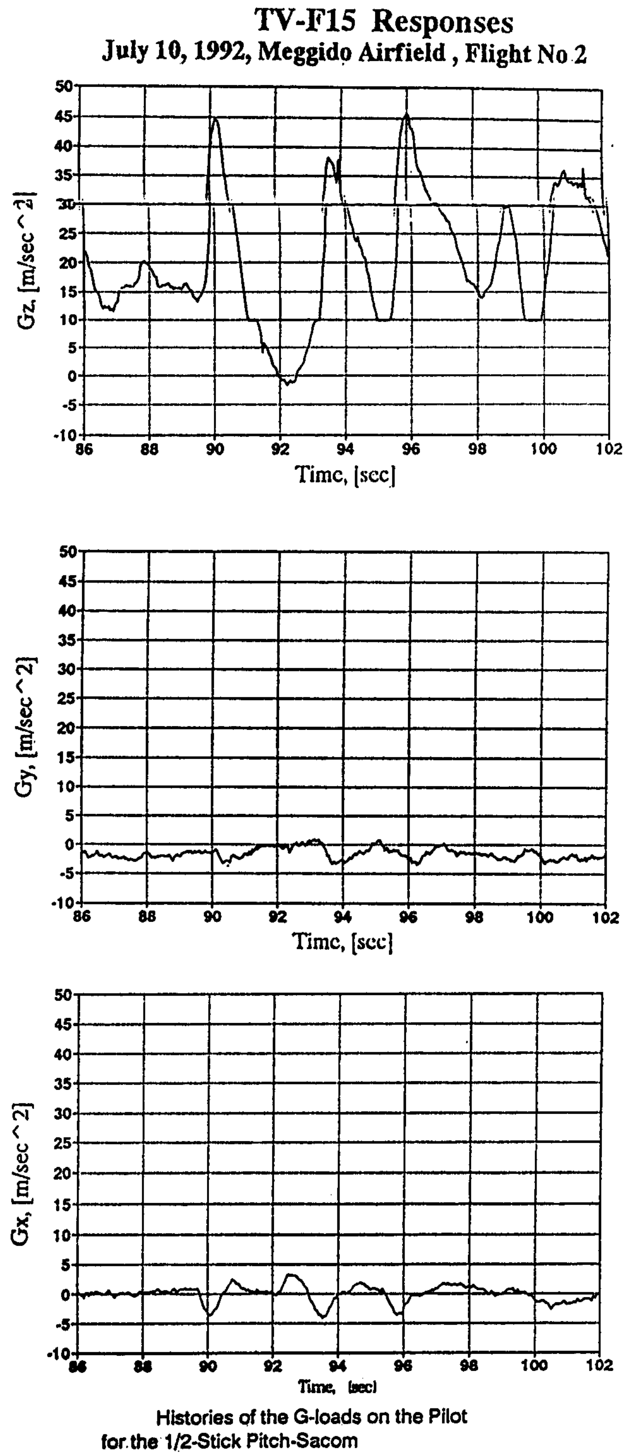


Figure 8. Pitch SACOM - G Profiles

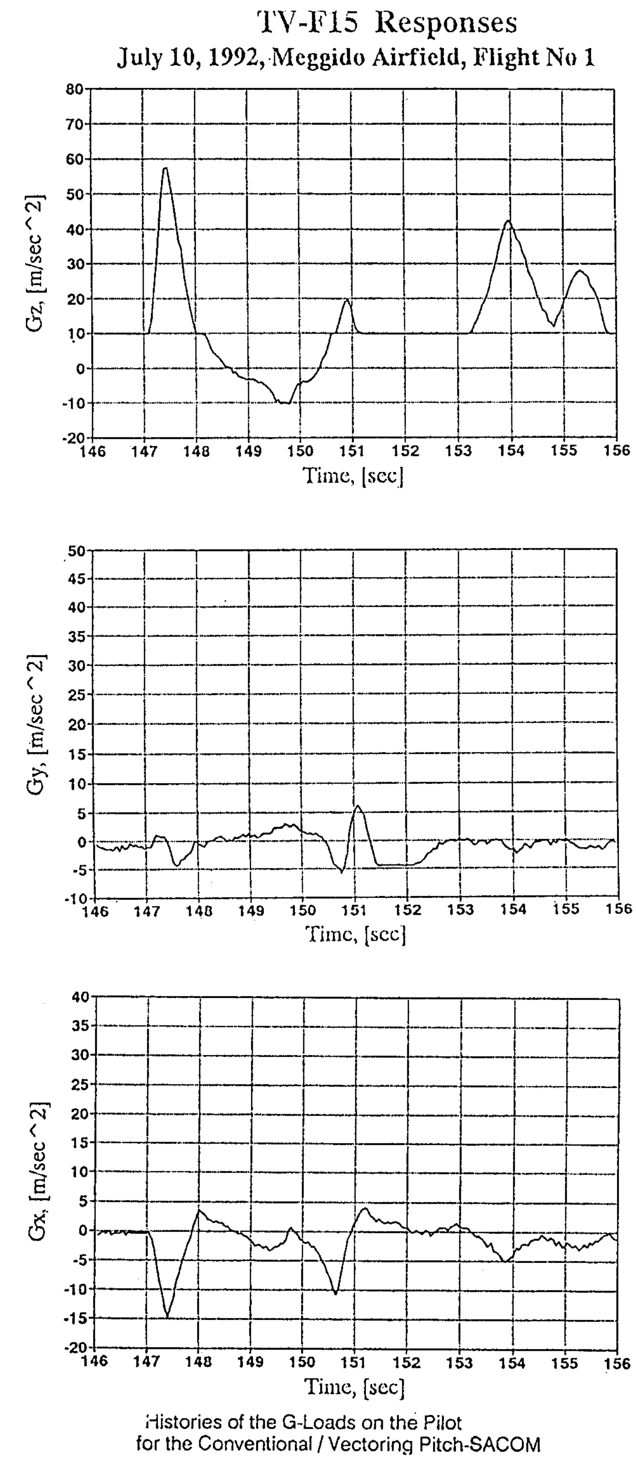


Figure 9. Cobra Type Maneuver - G Profiles

SUMMARY AND CONCLUSIONS

Data were delivered to Armstrong Laboratory AL/CFBS from an extensive study conducted at the IIT Technion. Ten maneuvers were considered and a host of such data exists in-house. This effort involved a complex investigation involving a foreign country, the Jet Propulsion Laboratory at the Technion, Israel Institute of Technology (IIT). The completion of this effort was greatly assisted by a Window on Europe program involving Captain D. D. Baumann of Wright Laboratory. From the data delivered to AL/CFBS, this important database provides a valuable baseline to simulate supermaneuvers on the DES centrifuge.

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